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PHASE-MATCHED FILTERS: APPLICATION TO THE STUDY OF LOVE WAVES

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ABSTRACT

Seismic surface waves are usually composed of overlapping wave trains representing multi-path propagation. A first task in the analysis of such waves is to identify and separate the various component wave trains so that each can be analyzed separately.

Phase-matched filters are a class of linear filters in which the Fourier phase of the filter is made equal to that of a given signal. The authors previously ~~Herrin and Goforth (1977)~~ described an iterative technique which can be used to find a phase-matched filter for a particular component of a seismic signal. Application of the filters to digital records of Rayleigh waves allowed multiple arrivals to be identified and removed, and allowed recovery of the complex spectrum of the primary wave train along with its apparent group velocity dispersion curve.

A comparable analysis of Love waves presents additional complications. Love waves are contaminated by both Love and Rayleigh multipathing and by primary off-axis Rayleigh energy. In the case of explosions, there is much less energy generated as Love waves than as Rayleigh waves.

The applicability of phase-matched filtering to Love waves is demonstrated by its use on earthquakes occurring in

the Norwegian Sea and near Iceland and on a nuclear explosion in Novaya Zemlya. Despite severe multipathing in two of the three events, the amplitude and phase of each of the primary Love waves were recovered without significant distortion.

INTRODUCTION

Phase-matched filters have been defined (Herrin and Goforth, 1977) as a class of linear filters in which the Fourier phase of the filter is made equal to that of a given signal.

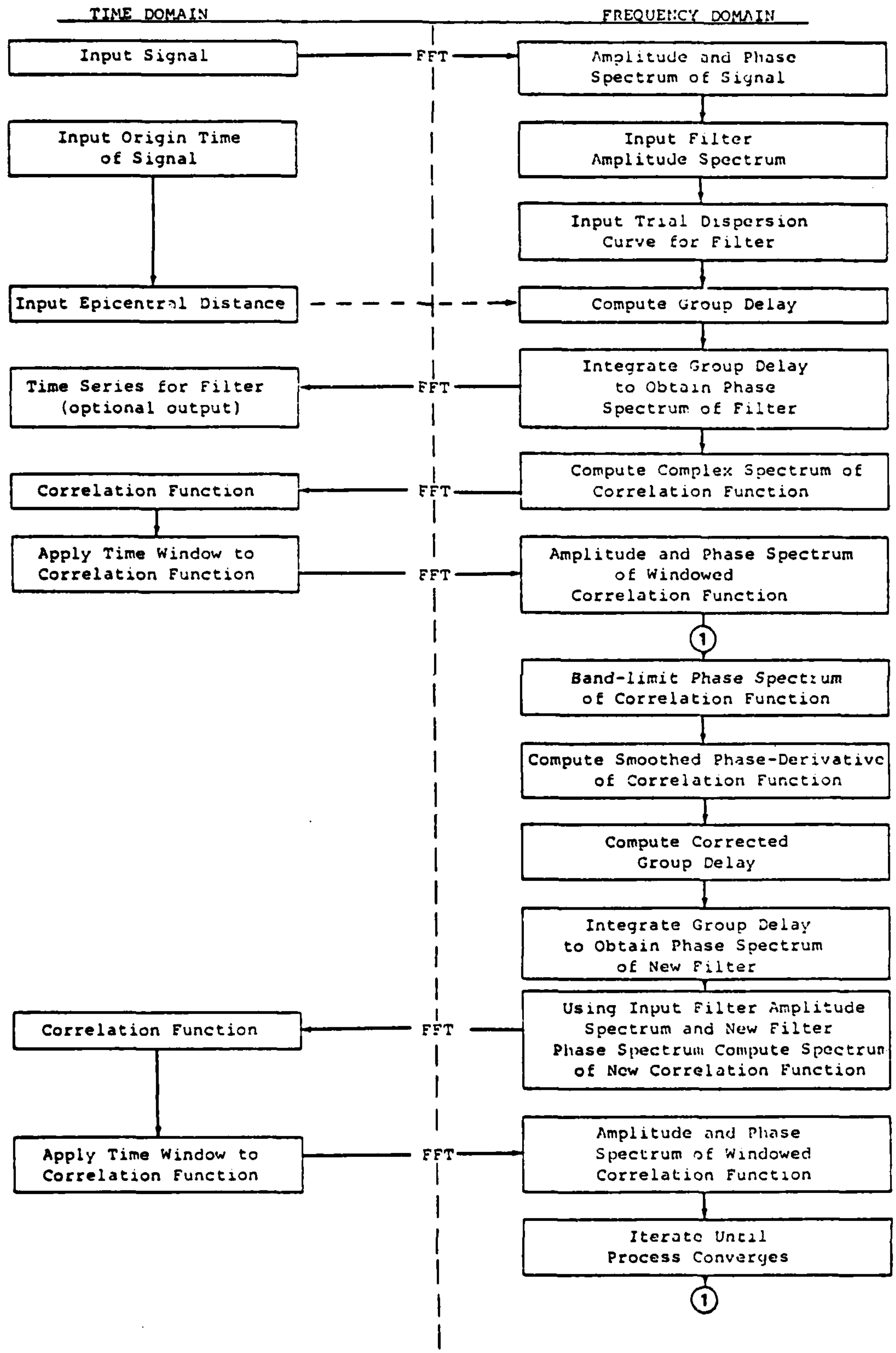
Consider the Fourier transform of the cross-correlation of a signal, s(t), with a time function, f(t), to be

$$s(t) \otimes f(t) \Longrightarrow |S(\omega)|\,|F(\omega)| \exp i[\sigma(\omega) - \phi(\omega)]$$

Now suppose that we choose fp(t) such that the Fourier phase is the same as that of s(t). We define the class of linear operators, fp(t), such that $\sigma(\omega) = \phi(\omega)$, as phase-matched filters with respect to the signal, s(t). The output of the above operation will then have the Fourier transform, $|S(\omega)|\,|Fp(\omega)|$, and will be an even function in the time domain as is the autocorrelation function. We call this output a pseudo-autocorrelation function (PAF). If means can be found for matching the Fourier phase of the signal and the filter, then the PAF will depend, for a given signal, only upon the amplitude spectrum of the particular phase-matched filter used in the operation. If $|Fp(w)|$ is chosen to be equal to $|S(w)|$, the phase-matched filter becomes the matched filter and maximizes the signal to noise power ratio assuming "white noise". The PAF becomes the autocorrelation function. At the other extreme, if $|Fp(w)|$ is chosen to be $1/|S(w)|$, the PAF becomes the impulse function. In practice, this choice would maximize the time resolution of the output but would greatly reduce the signal to noise ratio. If the signal to noise ratio of the signal is moderate to large, but the amplitude spectrum is unknown, a useful choice for the filter is $|Fp(w)| = 1$, the "white" filter.

In many cases, seismic signals are composed of two or more components overlapping in time. For example, Rayleigh and Love waves are almost always composed of overlapping wave trains representing multi-path propagation. A first task in the analysis of seismic surface waves is to identify and separate the various component wave trains so that each can be analyzed separately. Herrin and Goforth (1977) described an iterative technique which can be used to find a phase-matched filter for a particular component of a seismic signal. A flow diagram of the technique is shown in Table 1. They applied this process to digital records of Rayleigh waves from an earthquake and an explosion. Application of the filters allowed multiple arrivals to be identified and removed, and allowed recovery of the complex spectrum of the primary wave train along with its apparent group velocity dispersion curve.

TABLE 1
FLOW DIAGRAM



The amplitude spectrum of the primary signal obtained by this linear process was not contaminated by interference from the multipath arrivals.

The purpose of the present paper is to extend the applicability of phase-matched filtering to Love waves.

The analysis of Love waves presents problems which are not present in a comparable analysis of the vertical component of Rayleigh waves. For example, Love waves are contaminated not only by Love multipathing but also by Rayleigh multipathing. Love waves often arrive at a recording station from an azimuth differing significantly from that of the primary Rayleigh, with neither of them necessarily arriving along a great circle path. As a result, rotation of the horizontal components of the seismogram to be radial and transverse to the great circle path or even to the direction of arrival of the primary Love (if it can be determined) will not preclude the Rayleigh being strongly recorded on the transverse as well as on the radial component. There results a contamination of the mid- and short-period portion of the Love wave train.

PHASE-MATCHED FILTERING OF LOVE WAVES

Earthquakes occurring in the Norwegian Sea and near Iceland and a nuclear explosion in Novaya Zemlya have been selected to illustrate a new approach to the analysis of Love waves which deals directly with the problems outlined above. Table 2 gives the epicentral information for the events. The data were recorded digitally at the Seismic Research Observatory (SRO) at Albuquerque, New Mexico. The effects of atmospheric pressure changes were eliminated by the bore-hole installation of Geotech 36,000 seismometers at a depth of 100 meters; the quality of the data is excellent.

A three-component seismogram of an earthquake originating in the Norwegian Sea is shown in Figure 1. The horizontal components represent motion radial and transverse to the great circle through Albuquerque and the epicenter. A strong well-dispersed Rayleigh wave is easily identified on the vertical and radial seismograms, but interpretation of the motion on the transverse component as a Love wave is not so obvious. There is no clear dispersion, nor is it easy to see any energy arriving earlier than the long-period Rayleigh on the radial. The transverse amplitude is about 12 dB less than the radial.

Figures 2, 3, and 4 show multiple filter analyses

TABLE 2

EVENT	ORIGIN TIME	LAT	LONG	DISTANCE	m_b	DEPTH	RECORDING SITE
Norwegian Sea	1976-195-16-59-52.6	72.68N	3.72E	62.68	5.0	33	Albuquerque
Iceland	1975-359-22-04-35.1	66.14N	16.45W	58.63	5.1	10	Albuquerque
Novaya Zemlya	1975-294-11-59-57.3	73.35N	55.08E	71.28	6.5	0	Albuquerque

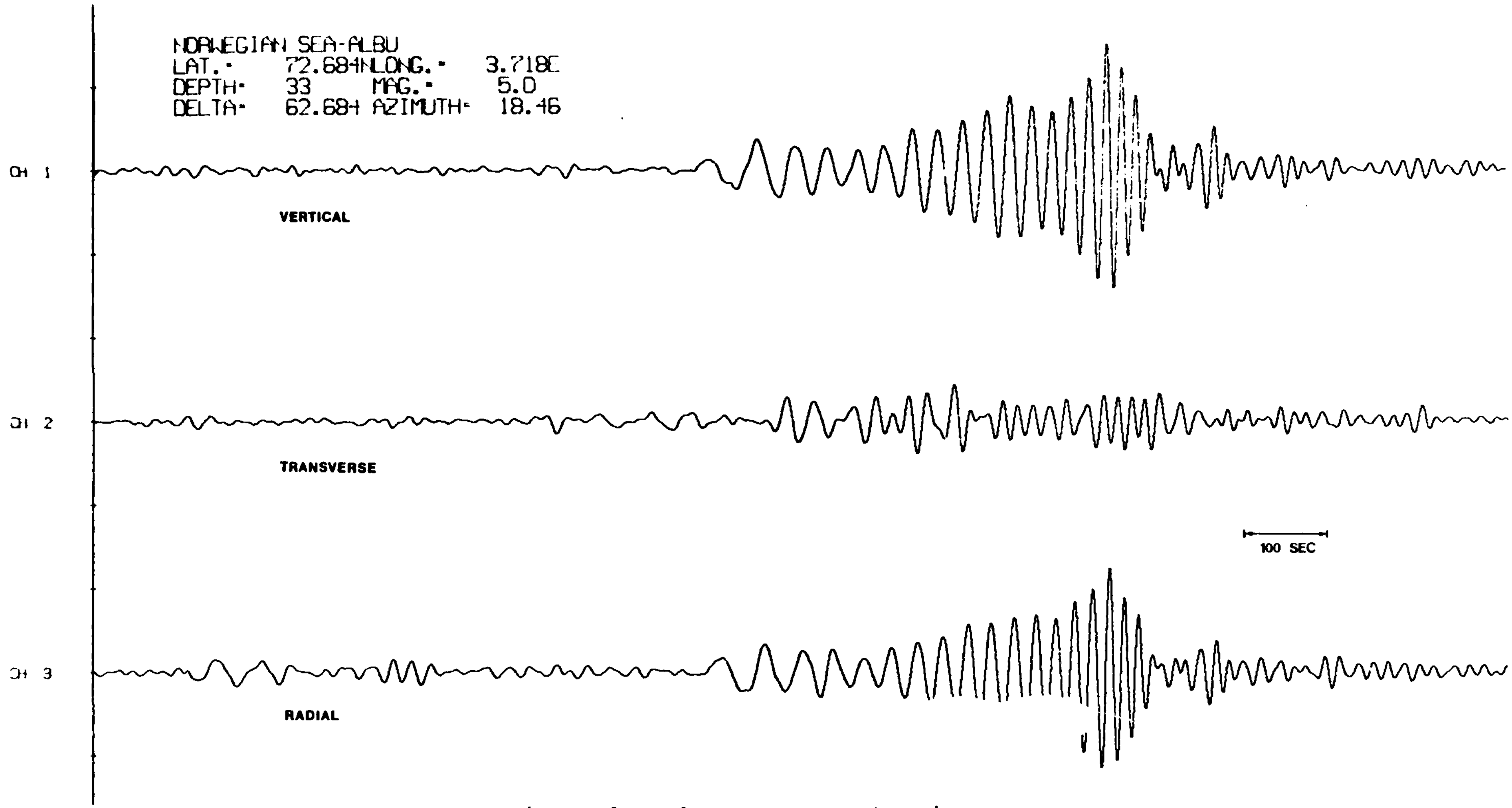


Figure 1. Three-component seismogram of the Norwegian Sea earthquake as recorded at Albuquerque, New Mexico.

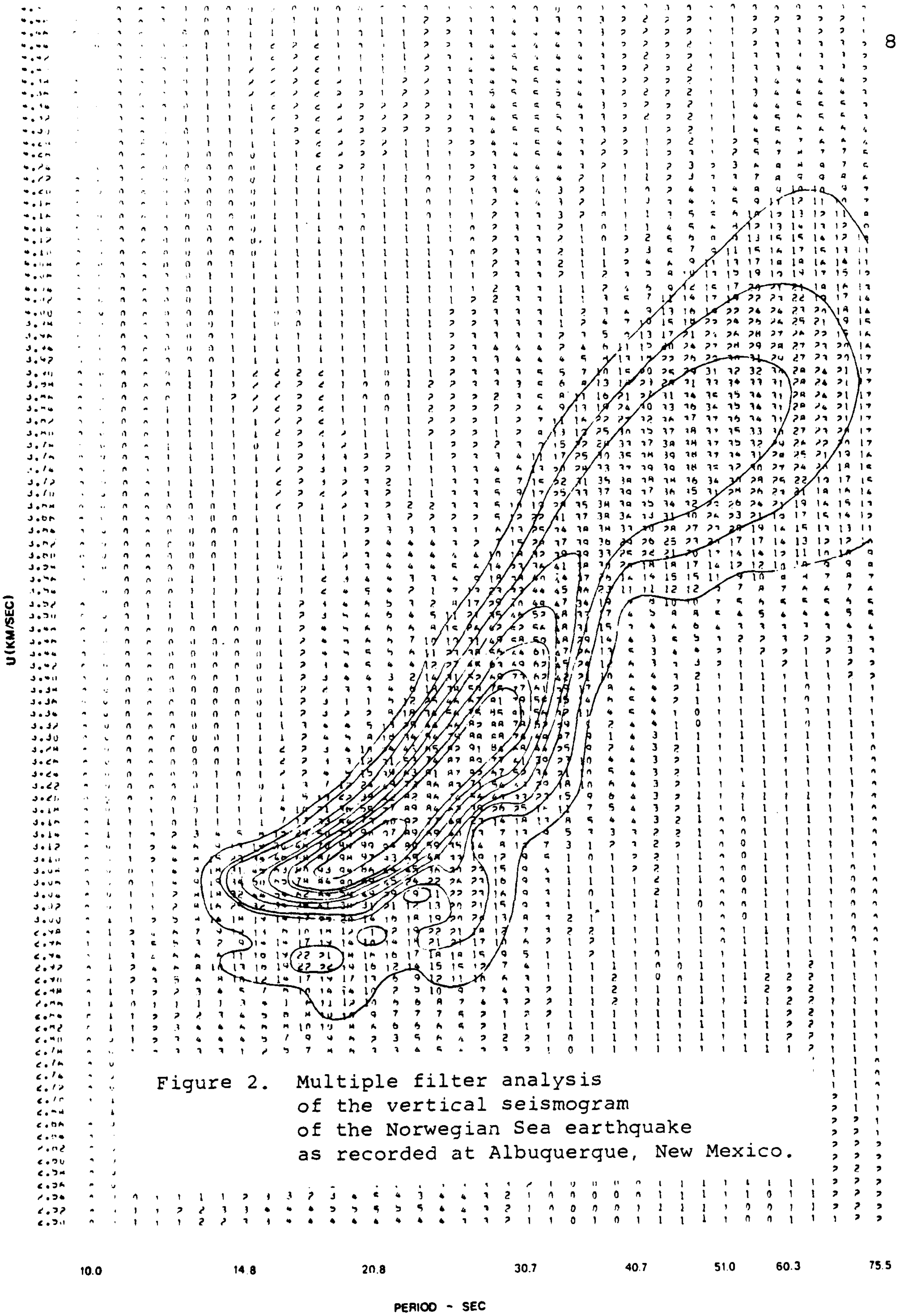


Figure 2. Multiple filter analysis of the vertical seismogram of the Norwegian Sea earthquake as recorded at Albuquerque, New Mexico.

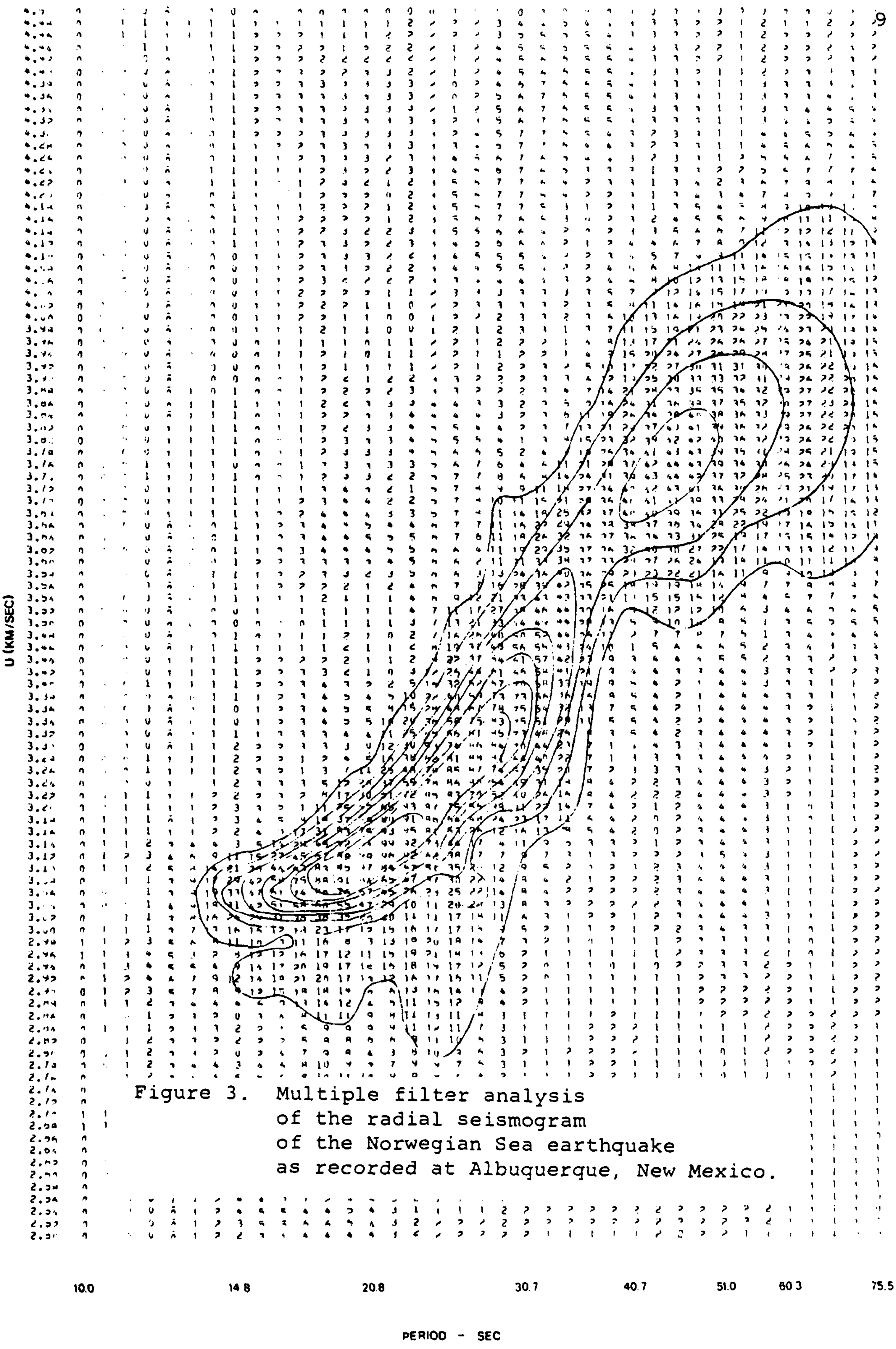


Figure 3. Multiple filter analysis of the radial seismogram of the Norwegian Sea earthquake as recorded at Albuquerque, New Mexico.

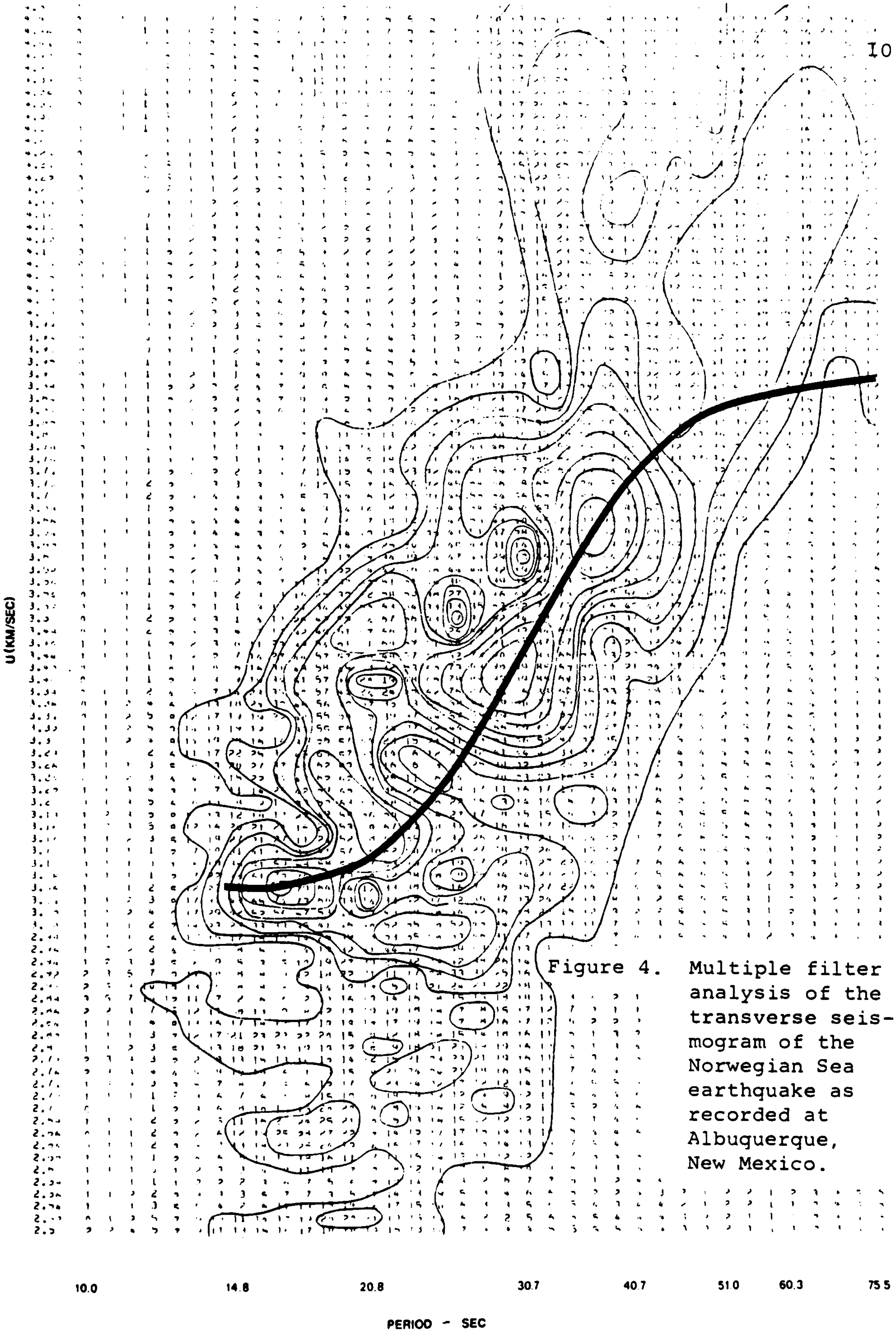


Figure 4. Multiple filter analysis of the transverse seismogram of the Norwegian Sea earthquake as recorded at Albuquerque, New Mexico.

(Dziewonski, Bloch, and Landisman, 1969) of the three components. On the vertical and radial analyses, the symmetry and relief of the contours would allow the analyst to obtain an excellent estimate of the apparent Rayleigh dispersion curve by inspection. In fact, the absence of "holes" and "build-ups" in amplitude along the center of symmetry indicates that a very reliable estimate of the amplitude spectrum of the primary Rayleigh, without distortion from multipathing, could be obtained from multiple filter analysis of either the vertical or the radial components.

The multiple filter analysis of the transverse component shown in Figure 4 is much less diagnostic. The Rayleigh dispersion curve obtained from filters phase-matched to the other two components is superimposed on the contours. It is clear that a significant portion of the motion observed on the transverse component is Rayleigh energy, presumably arriving at Albuquerque from a direction differing substantially from the great circle path. Love wave energy can be seen arriving earlier than the Rayleigh, but it is not possible to obtain a dispersion curve or an amplitude spectrum using the multiple filter analysis. This is especially true in the period band 30 to 45 seconds where the off-axis Rayleigh completely obscures the Love arrival.

Phase-matched filtering provides the resolution necessary to extract the Love wave energy from the transverse seismogram.

Using a trial dispersion curve obtained from the multiple filter analysis, and following the iterative procedure outlined in Table 1, the pseudo-autocorrelation function (PAF) shown in Figure 5 was obtained. The Love wave PAF has zero phase, resulting from correlation of the seismogram with the phase-matched filter, and, properly windowed, has the amplitude spectrum of the primary Love wave undistorted by multipaths or off-axis Rayleigh waves. The derivative of the phase of the phase-matched filter is the group delay and, when combined with the origin time and epicentral distance, yields the apparent group velocity dispersion curve. Figure 6 shows the spectral amplitude before and after phase-matched filtering. The dotted spectrum in Figure 6 was obtained by taking the Fourier transform of a 100-second window centered on the Love PAF in Figure 5. The spectra are not corrected for instrument response. Since both the amplitude and the phase have been determined, the time domain representation of the primary Love wave can be obtained by the inverse Fourier transform. Figure 7 shows the original transverse seismogram and the Love wave obtained by phase-matched filtering plotted at the same gain. The filtered Love wave is undistorted by off-axis primary Rayleigh or by Love or Rayleigh multipathing. Its signal to noise amplitude ratio has been enhanced by approximately 10 dB. The presentation of the filtered Love wave in the time domain, although providing no information not previously ob-

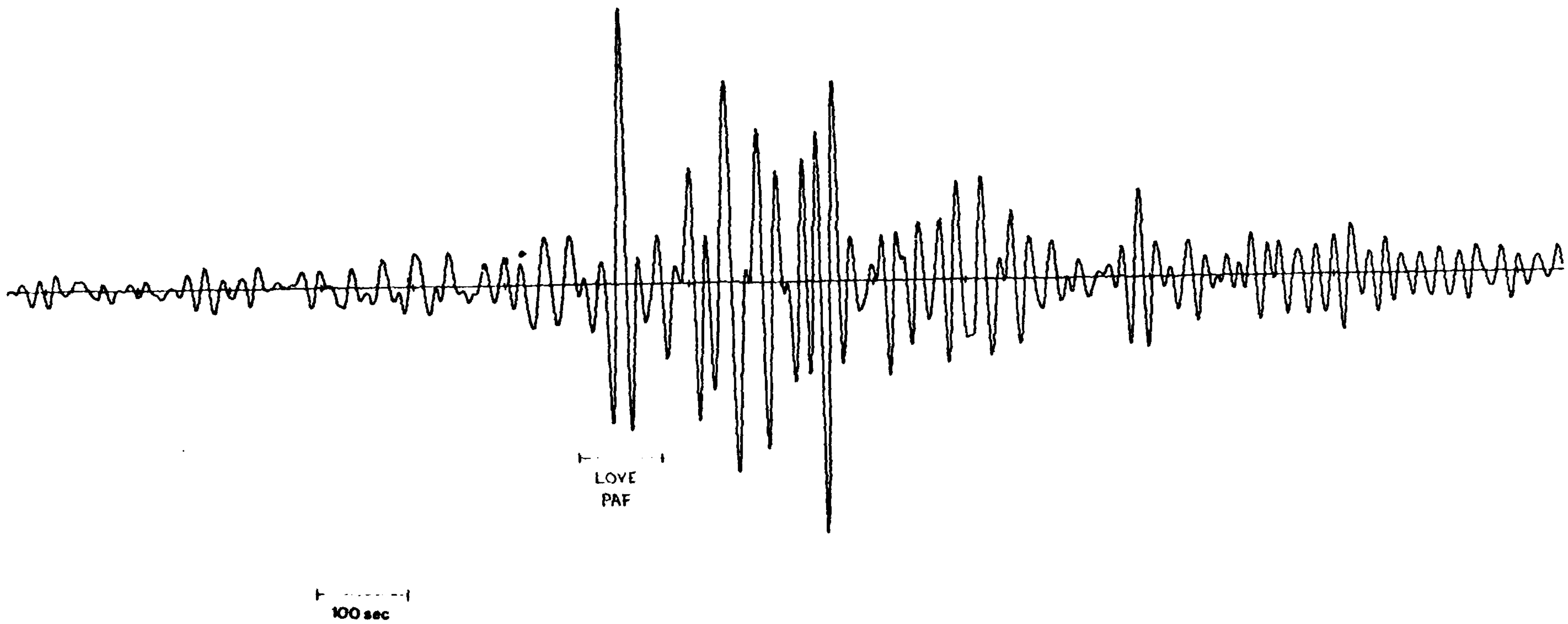


Figure 5. Pseudo-autocorrelation function obtained for the Love wave on the transverse seismogram of the Norwegian Sea earthquake.

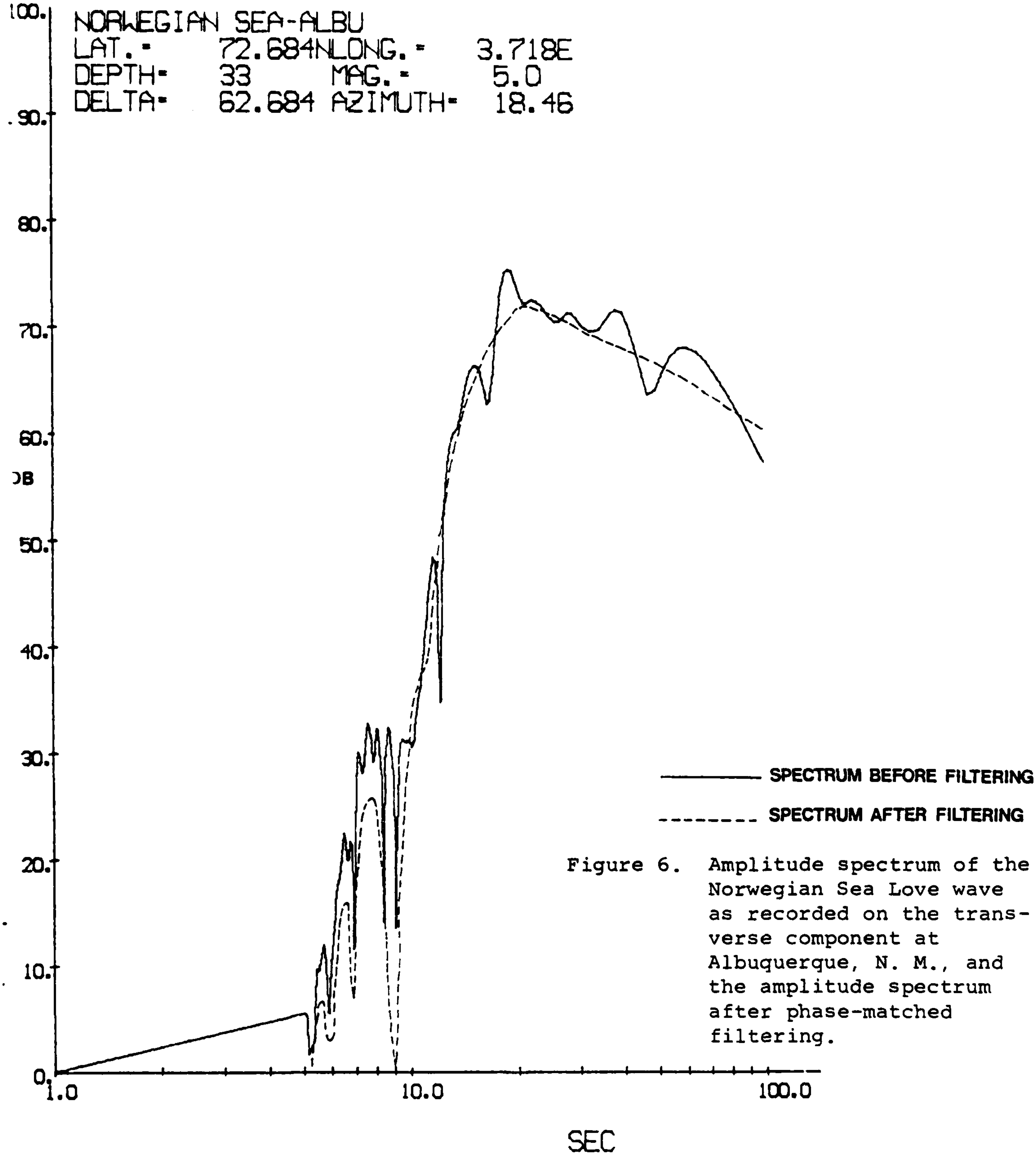


Figure 6. Amplitude spectrum of the Norwegian Sea Love wave as recorded on the transverse component at Albuquerque, N. M., and the amplitude spectrum after phase-matched filtering.

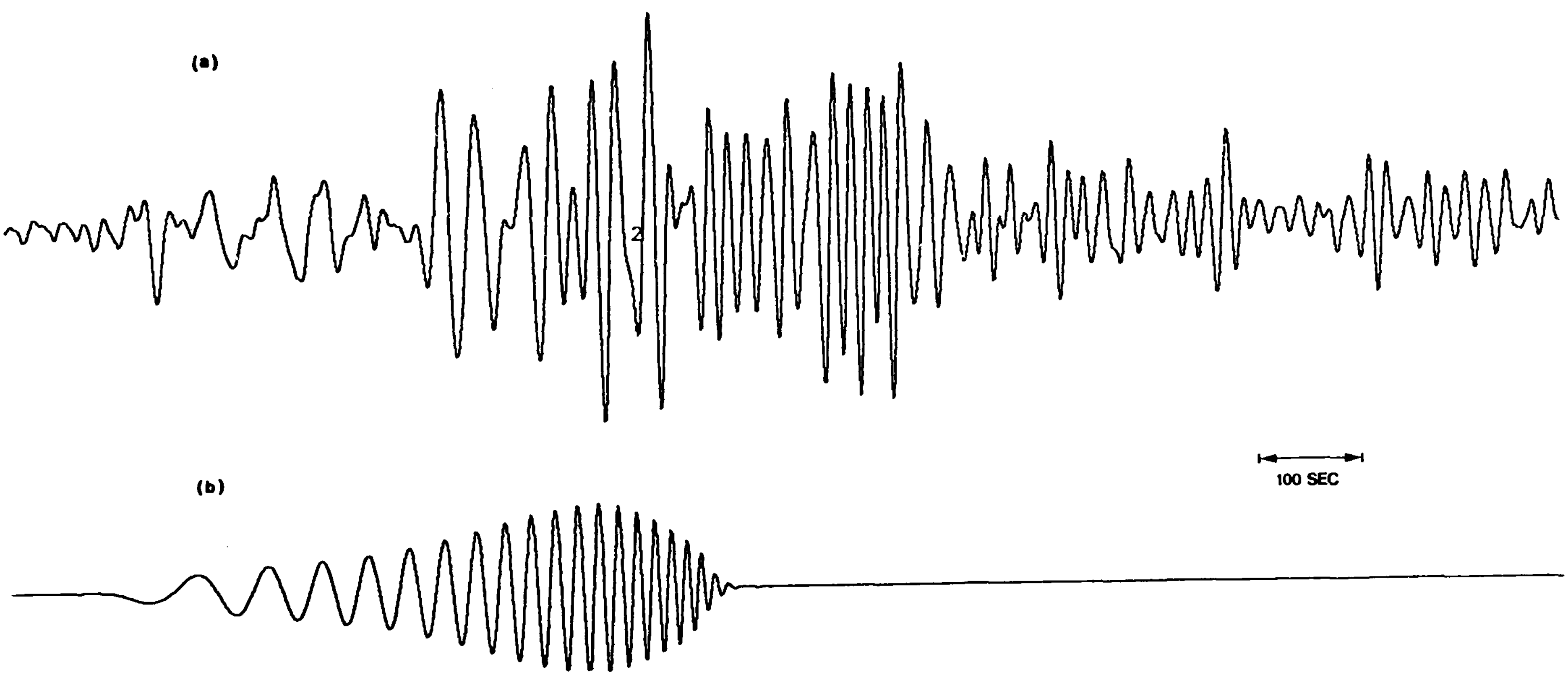


Figure 7. The Norwegian Sea transverse seismogram recorded at Albuquerque, N. M., and the Love wave obtained from it by phase-matched filtering.

tained in spectral form, is a dramatic demonstration of both the degree to which the signal was distorted and the resolution of phase-matched filtering.

Although it is not necessary in the particular case of the Norwegian Sea earthquake, phase-matched filtering offers another interesting approach to the problem of extracting the Love wave train. First, the phase-matched filter for the primary Rayleigh wave is found on the vertical component, where Rayleigh multipaths are the only interference. A phase shift of this filter by 90° at all frequencies will result in a phase-matched filter for the horizontal component of the Rayleigh signal. Applying the latter filter to the transverse seismogram provides the phase and amplitude spectra of the horizontal Rayleigh motion; the inverse Fourier transform yields its time domain representation, which can be directly subtracted from the transverse seismogram. Following this procedure, Figure 8a shows the PAF obtained for the Rayleigh on the vertical seismogram. Note the multipath peaks lagging the primary PAF by about 60 to 200 seconds. Correlation of the same filter advanced by 90° at all frequencies with the transverse seismogram yields the PAF shown in Figure 8b. The Rayleigh PAF in 8b is preceded by mis-matched Love and Love multipath oscillations and is followed by Rayleigh multipaths. Plots 8(a) and 8(b) are normalized such that the maximum amplitudes of the Rayleigh PAFs are equal. Thus, the apparently greater ampli-

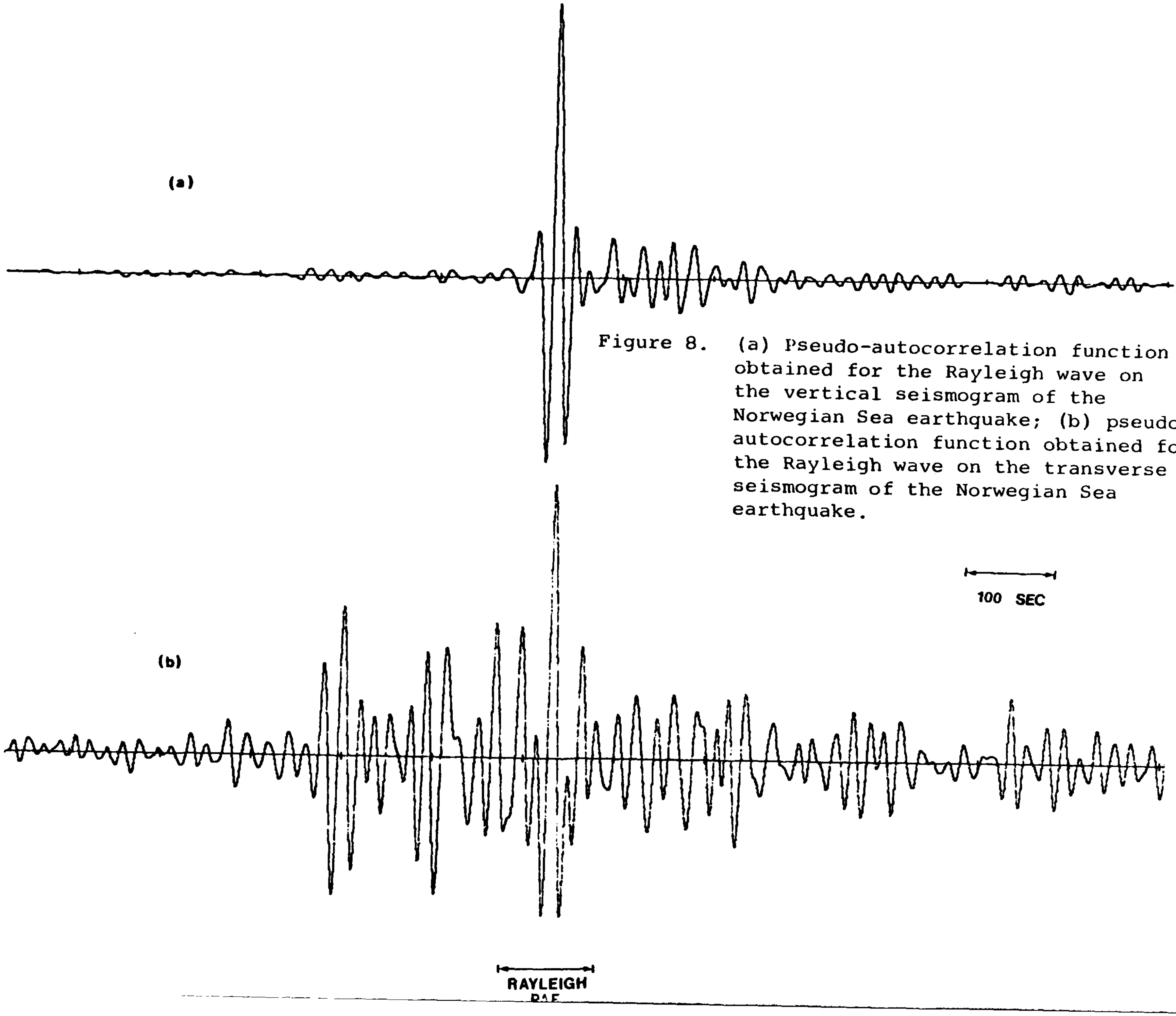


Figure 8. (a) Pseudo-autocorrelation function obtained for the Rayleigh wave on the vertical seismogram of the Norwegian Sea earthquake; (b) pseudo-autocorrelation function obtained for the Rayleigh wave on the transverse seismogram of the Norwegian Sea earthquake.

tudes of the Rayleigh multipaths on the transverse horizontal component (8(b)) than on the vertical (8(a)) are due to the scaling. The inverse transform of the windowed Rayleigh PAF in 8(b) is shown in Figure 9, along with the transverse seismogram and the difference between the two. A multiple filter analysis of the remainder trace is shown in Figure 10. With the transverse Rayleigh primary component removed, the Love amplitude contours are now sufficiently well defined that an analyst could obtain a good estimate (the dark line in Figure 10) of the dispersion curve, although a mid-period precursor and the Love and Rayleigh multipaths remain.

Seismograms of an earthquake occurring on the Mid-Atlantic Ridge near Iceland and recorded at Albuquerque show a very well-developed Love wave. Figure 11 shows the vertical, transverse, and radial seismograms. Analysis of this Love wave appears to present few of the difficulties encountered in the analysis of the Norwegian Sea event. The signal to noise ratio is excellent, and the Rayleigh off-axis arrivals are short-period and consequently well separated in time from the Love wave train. However, the amplitude spectrum of the Love wave train on the transverse seismogram, shown in Figure 12, contains a pattern of "holes" and "build-ups" which is consistent with the presence of weak multipath arrivals.

Application of the iterative phase-matching technique to the transverse component produced the correlation function

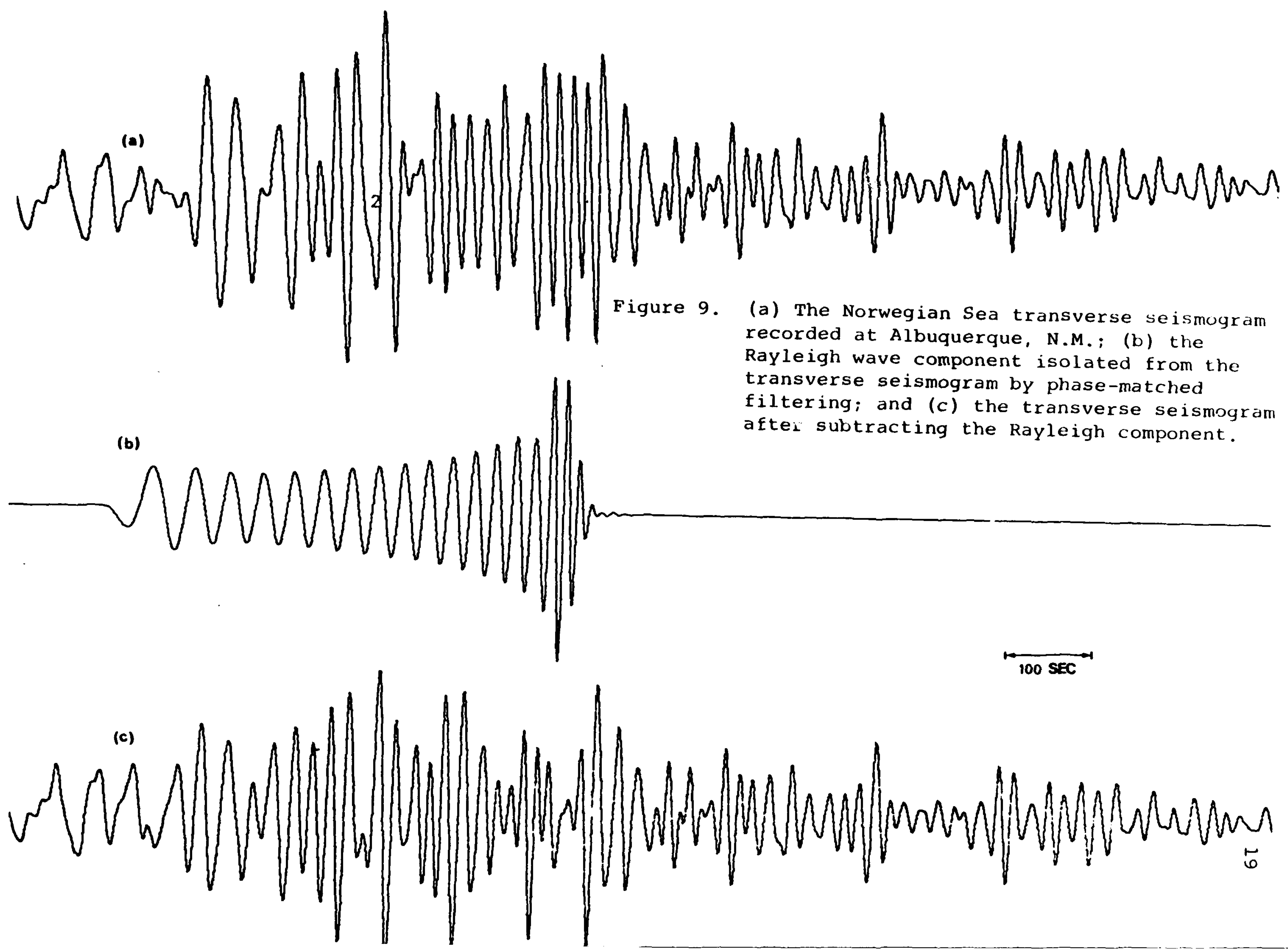


Figure 9. (a) The Norwegian Sea transverse seismogram recorded at Albuquerque, N.M.; (b) the Rayleigh wave component isolated from the transverse seismogram by phase-matched filtering; and (c) the transverse seismogram after subtracting the Rayleigh component.

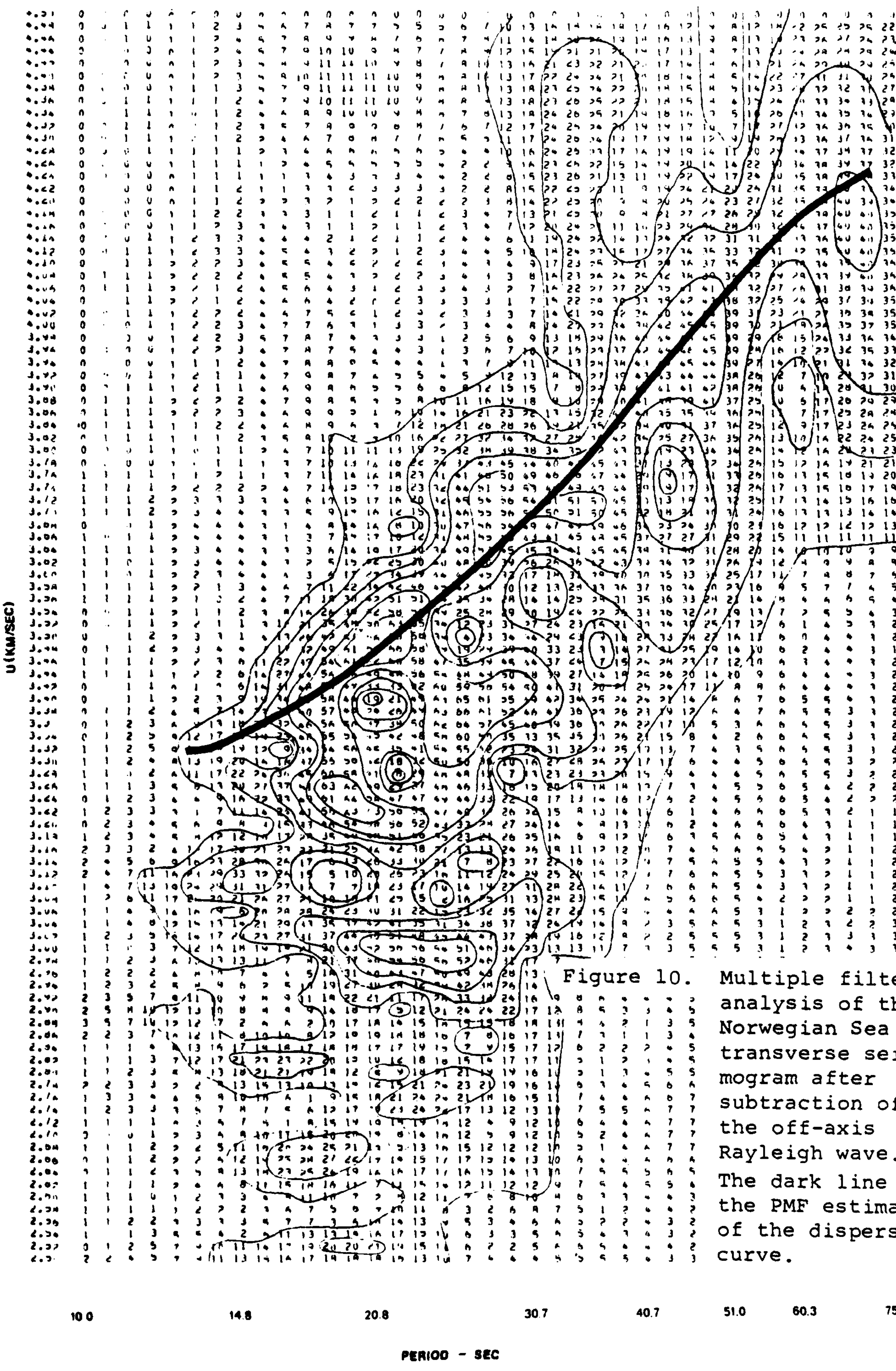


Figure 10. Multiple filter analysis of the Norwegian Sea transverse seismogram after subtraction of the off-axis Rayleigh wave. The dark line is the PMF estimate of the dispersion curve.

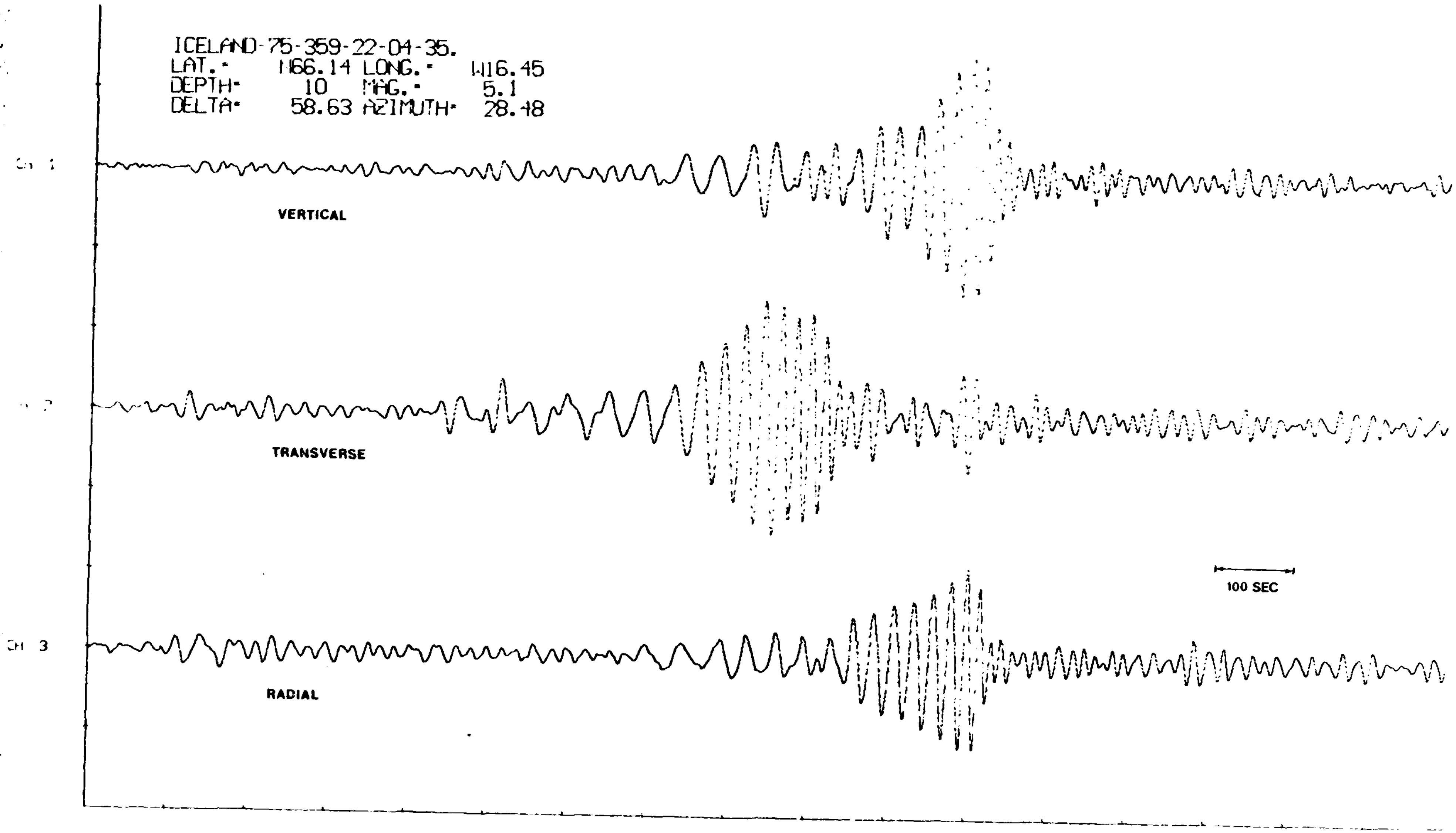


Figure 11. Three-component seismogram of the Iceland earthquake as recorded at Albuquerque, New Mexico.

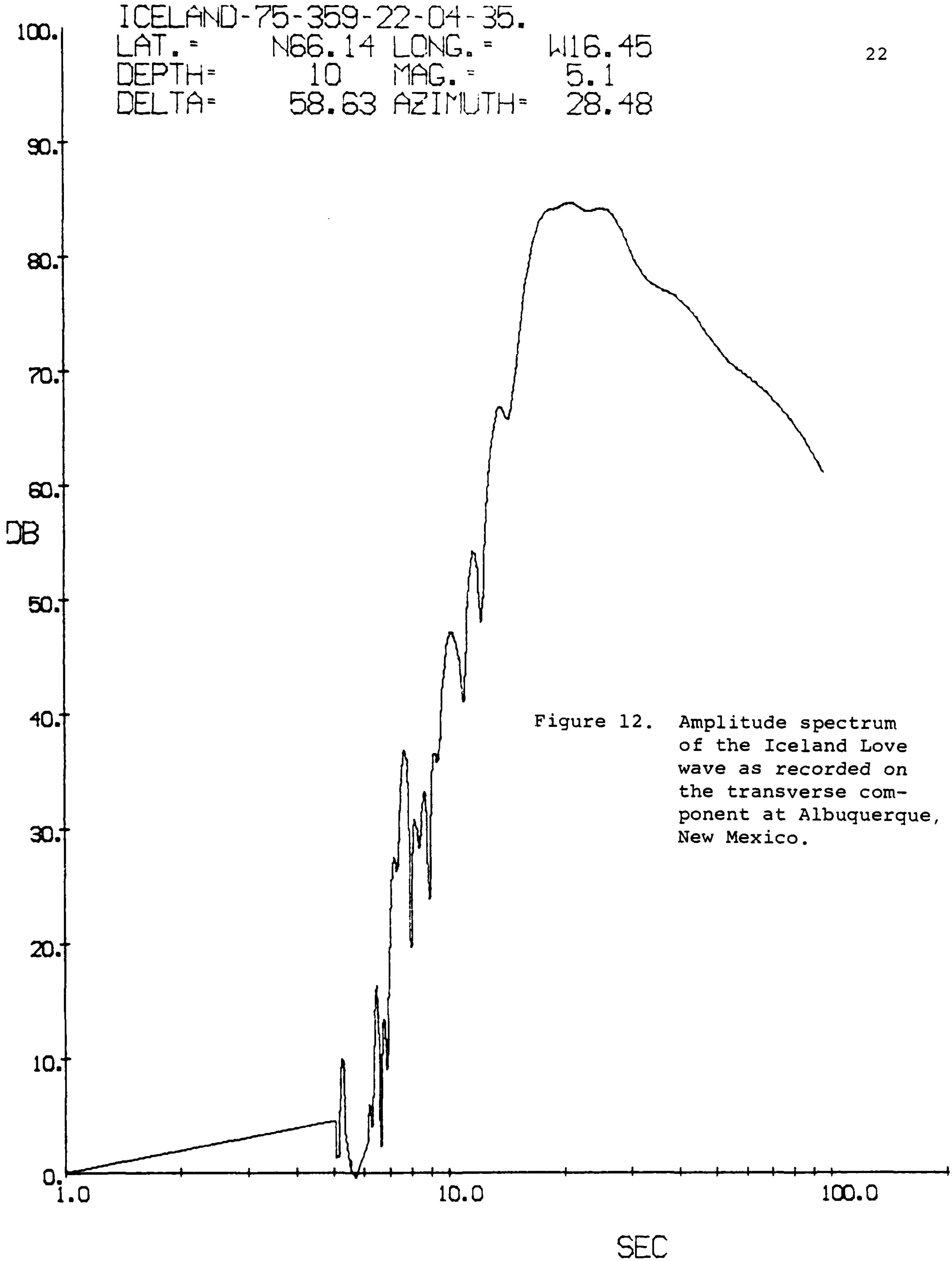


Figure 12. Amplitude spectrum of the Iceland Love wave as recorded on the transverse component at Albuquerque, New Mexico.

shown in Figure 13. The Love PAF is seen to be followed at about 50 to 250 seconds by low amplitude multipaths. A 100-second window centered about the PAF excludes the multipaths as well as any off-axis Rayleigh motion. The spectrum of the PAF and the previously-shown spectrum of the transverse component signal are shown in Figure 14. The difference in the two spectra is due to the removal of the multipaths. Applying the inverse Fourier transform to the amplitude and phase spectra obtained by PMF gives the time domain Love wave with the multipath removed. This signal, along with the original transverse seismogram, are plotted at the same gain in Figure 15. Comparing the two signals shows that the effect of the multipath in the time domain was to slightly modulate the amplitude of the wave train and to off-set some of the zero crossings.

An example of Love waves produced by a nuclear explosion is shown in Figure 16. The Love wave is well-defined on the transverse seismogram, although off-axis Rayleigh energy of period 15-20 seconds is also present. The amplitude spectrum of the wave train, excluding from the transform window the obvious Rayleigh motion, is shown in Figure 17. Again, the ragged nature of the spectrum is suggestive of multipathing. Application of phase-matched filtering produced the correlation function shown in Figure 18, and the Fourier transform of a 100-second window centered on the Love PAF produced the

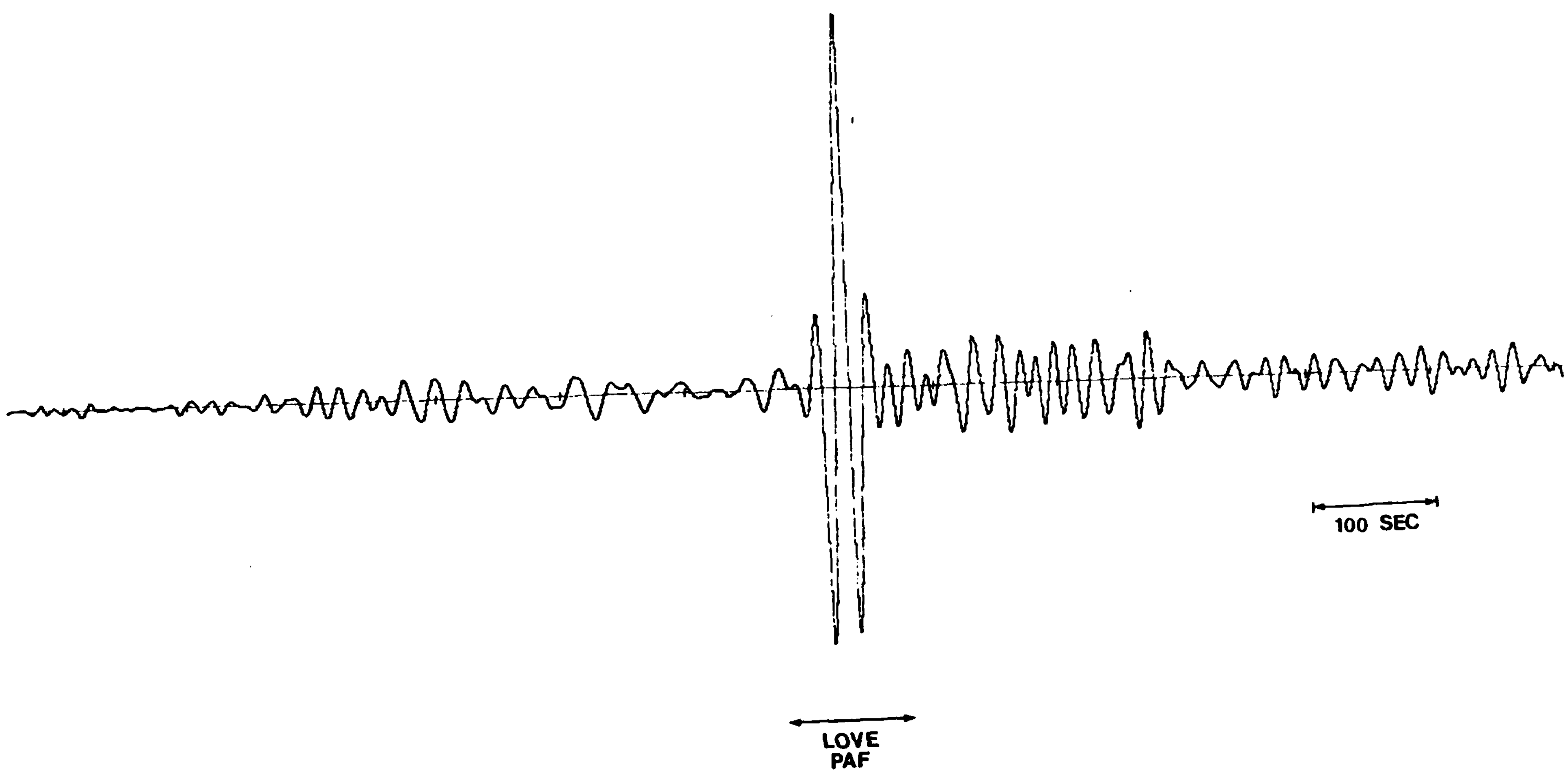


Figure 13. Pseudo-autocorrelation function obtained for the Love wave on the transverse seismogram of the Iceland earthquake.

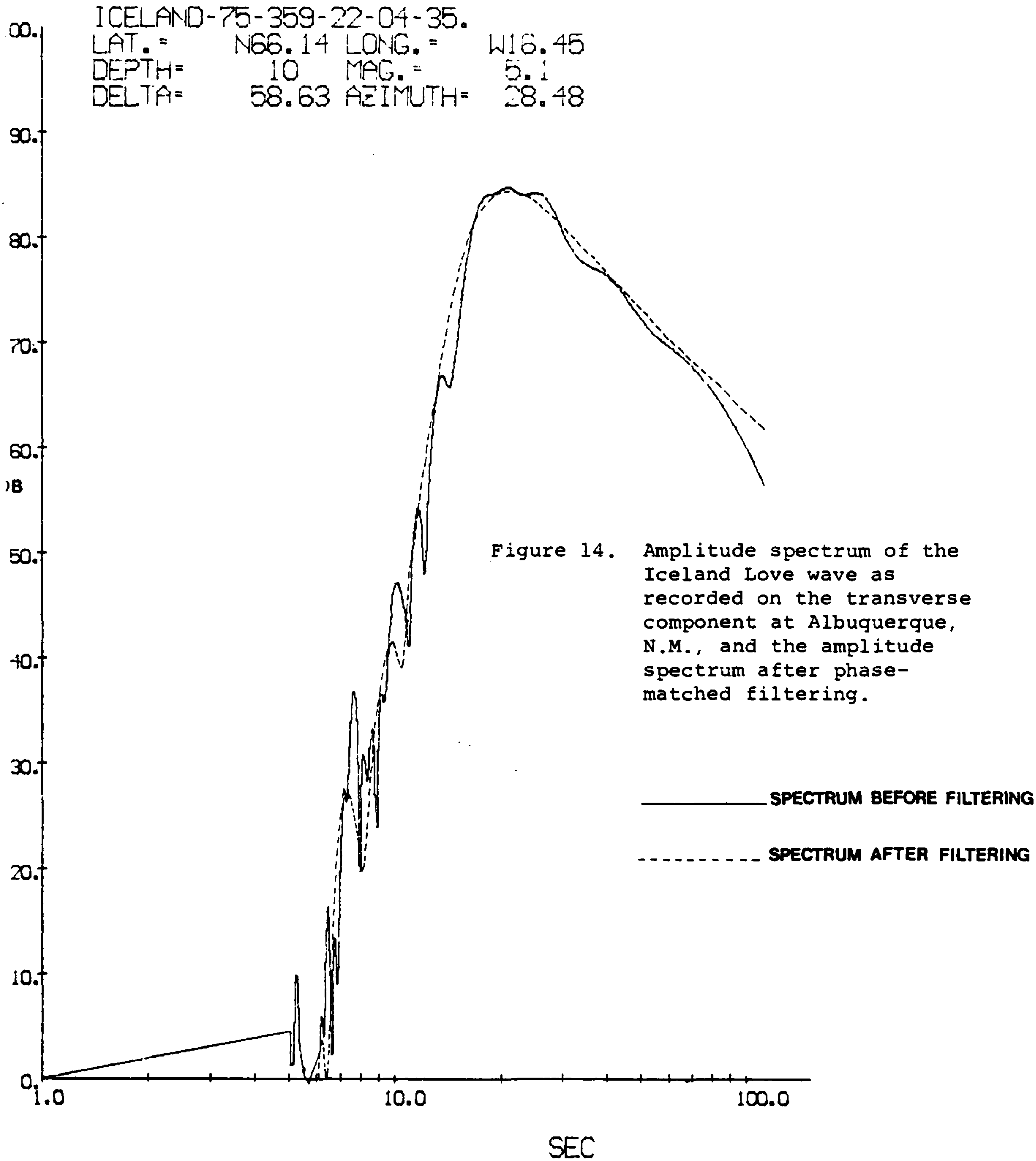


Figure 14. Amplitude spectrum of the Iceland Love wave as recorded on the transverse component at Albuquerque, N.M., and the amplitude spectrum after phase-matched filtering.

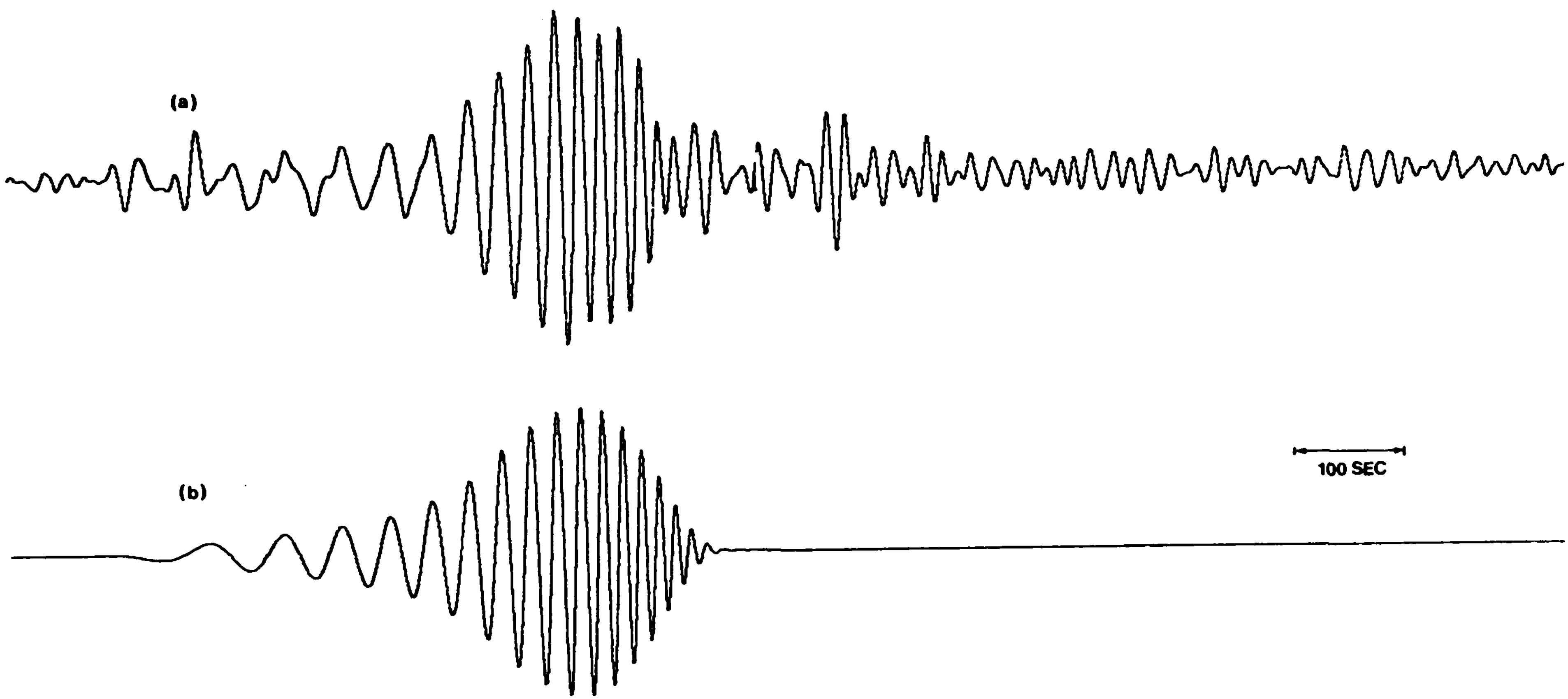


Figure 15. (a) The Iceland transverse seismogram recorded at Albuquerque, N.M., and (b) the Love wave obtained from it by phase-matched filtering.

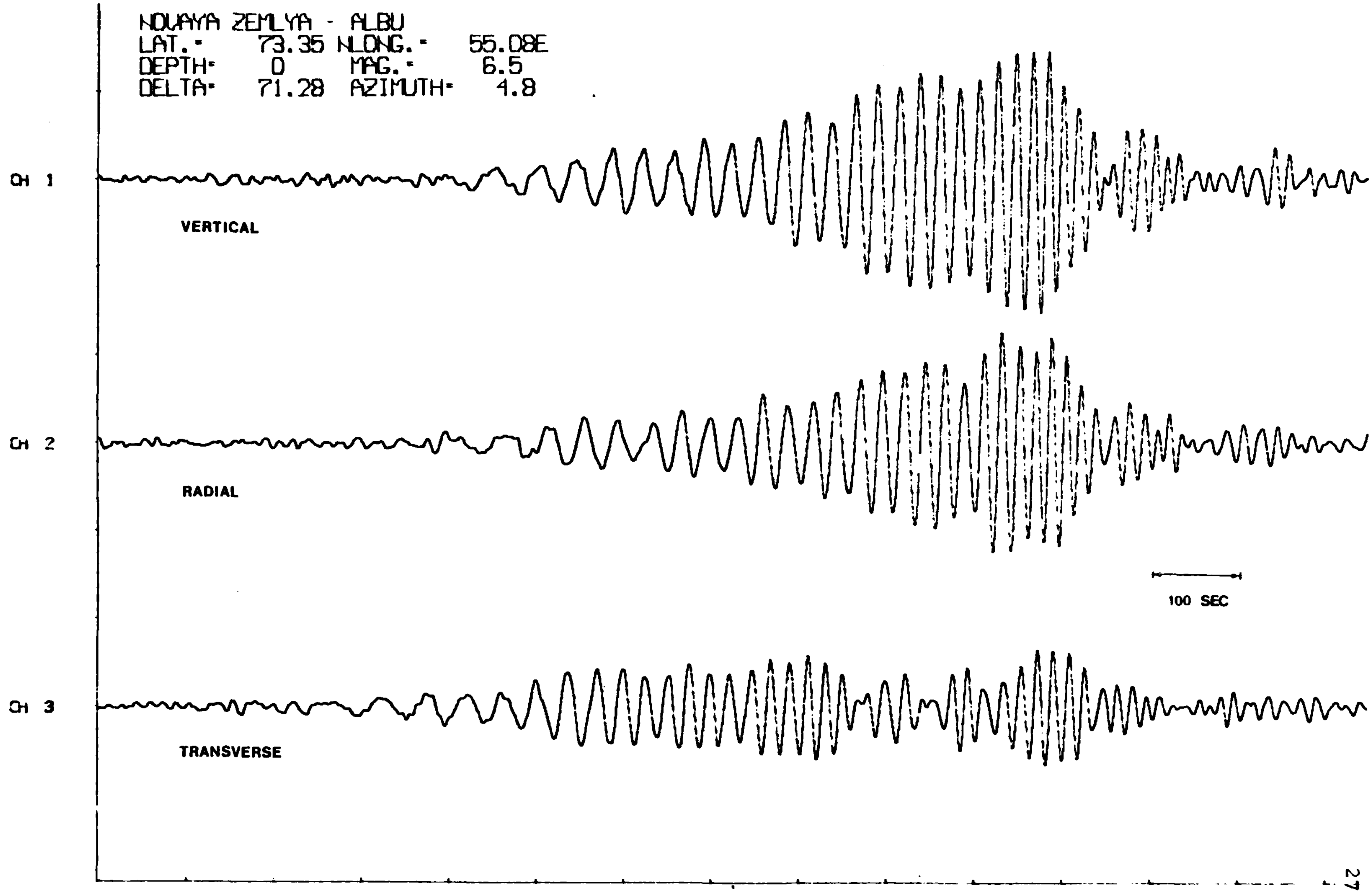


Figure 16. Three-component seismogram of the Novaya Zemlya nuclear explosion as recorded at Albuquerque, N.M.

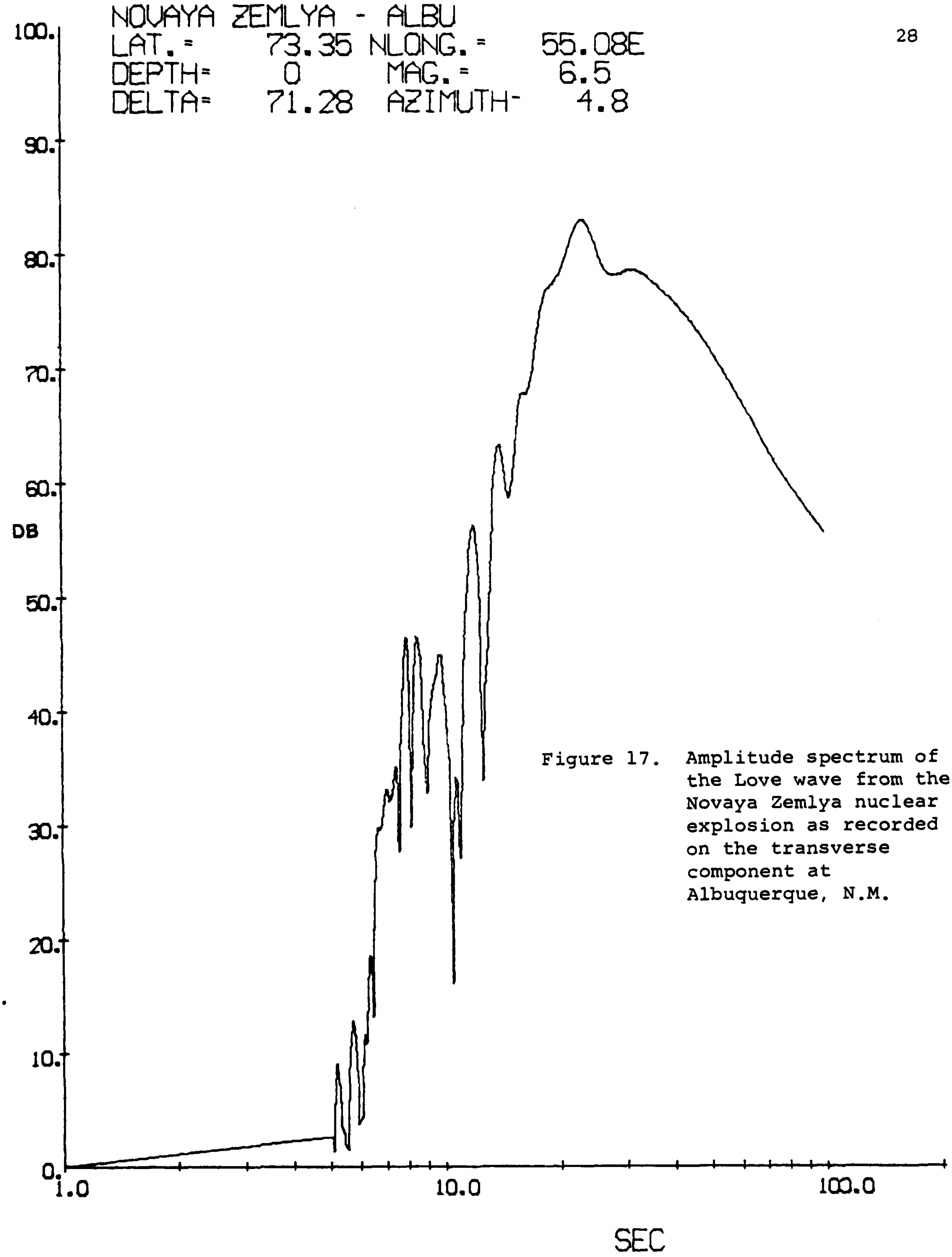


Figure 17. Amplitude spectrum of the Love wave from the Novaya Zemlya nuclear explosion as recorded on the transverse component at Albuquerque, N.M.

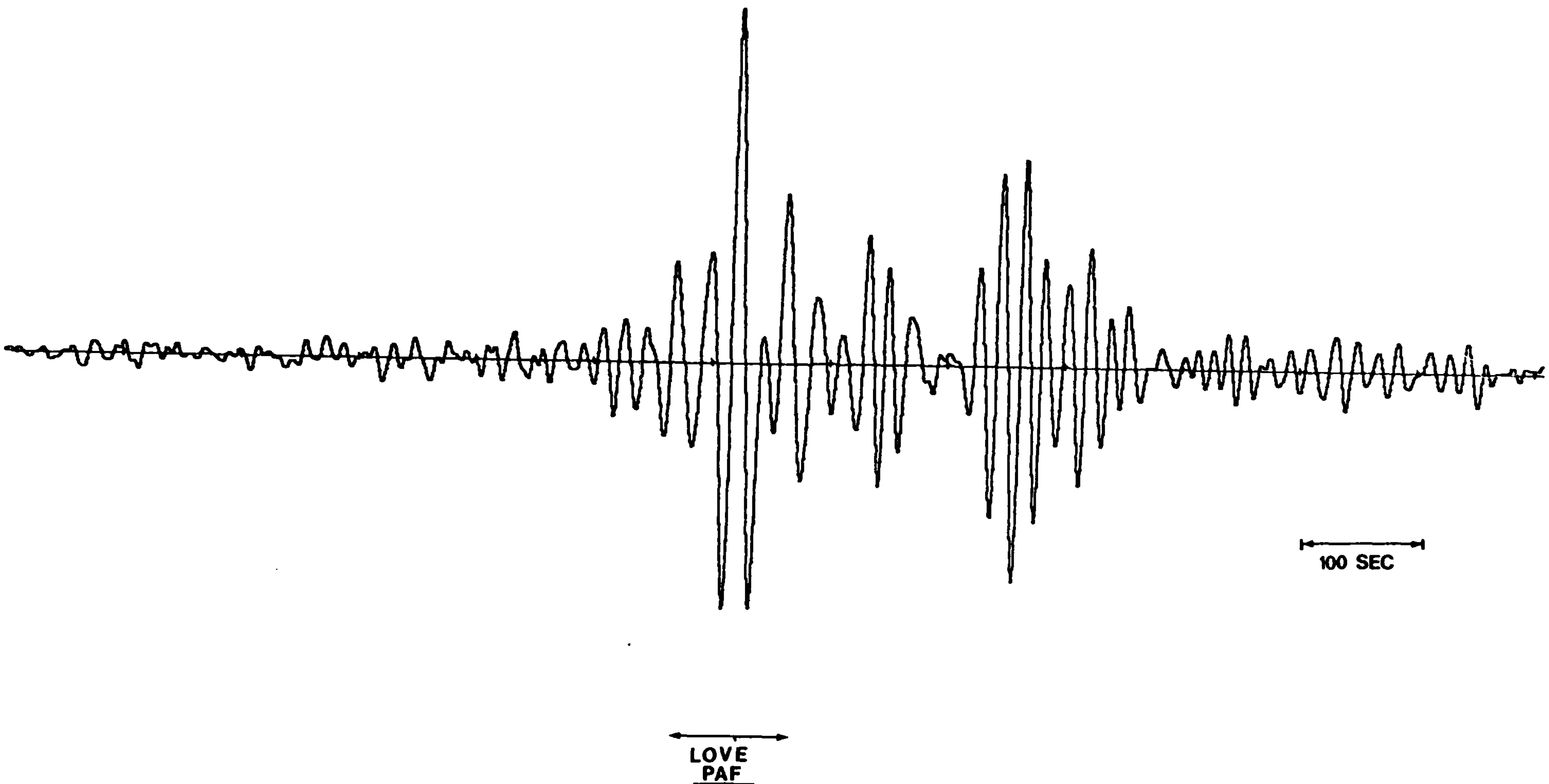


Figure 18. Pseudo-autocorrelation function obtained for the Love wave on the transverse seismogram of the Novaya Zemlya explosion.

spectrum shown in Figure 19. Also shown is the spectrum of the Love wave train taken before phase-matched filtering.

The apparent group velocity dispersion curves obtained by phase-matched filtering of the three events are shown in Figure 20. The group velocities for the similar paths Norwegian Sea-Albuquerque and Iceland-Albuquerque are almost the same. The maximum difference in velocity is 0.05 km/sec in the period range 10-15 seconds. However, these curves are free of multi-path bias, and the phase-matching process is extremely precise. Known velocities of simulated signals can be recovered to within $\pm$ 0.005 km/sec; therefore, the 0.05 km/sec difference is thought to represent real differences along the travel paths The Novaya Zemlya-Albuquerque path has a dispersion curve that is significantly different from the other two, even at periods of 100 seconds. The great circle path for this event lies mainly on the continental crust crossing Greenland, Canada and the central United States. The last segment of the path traverses the Front Range of the Rocky Mountains.

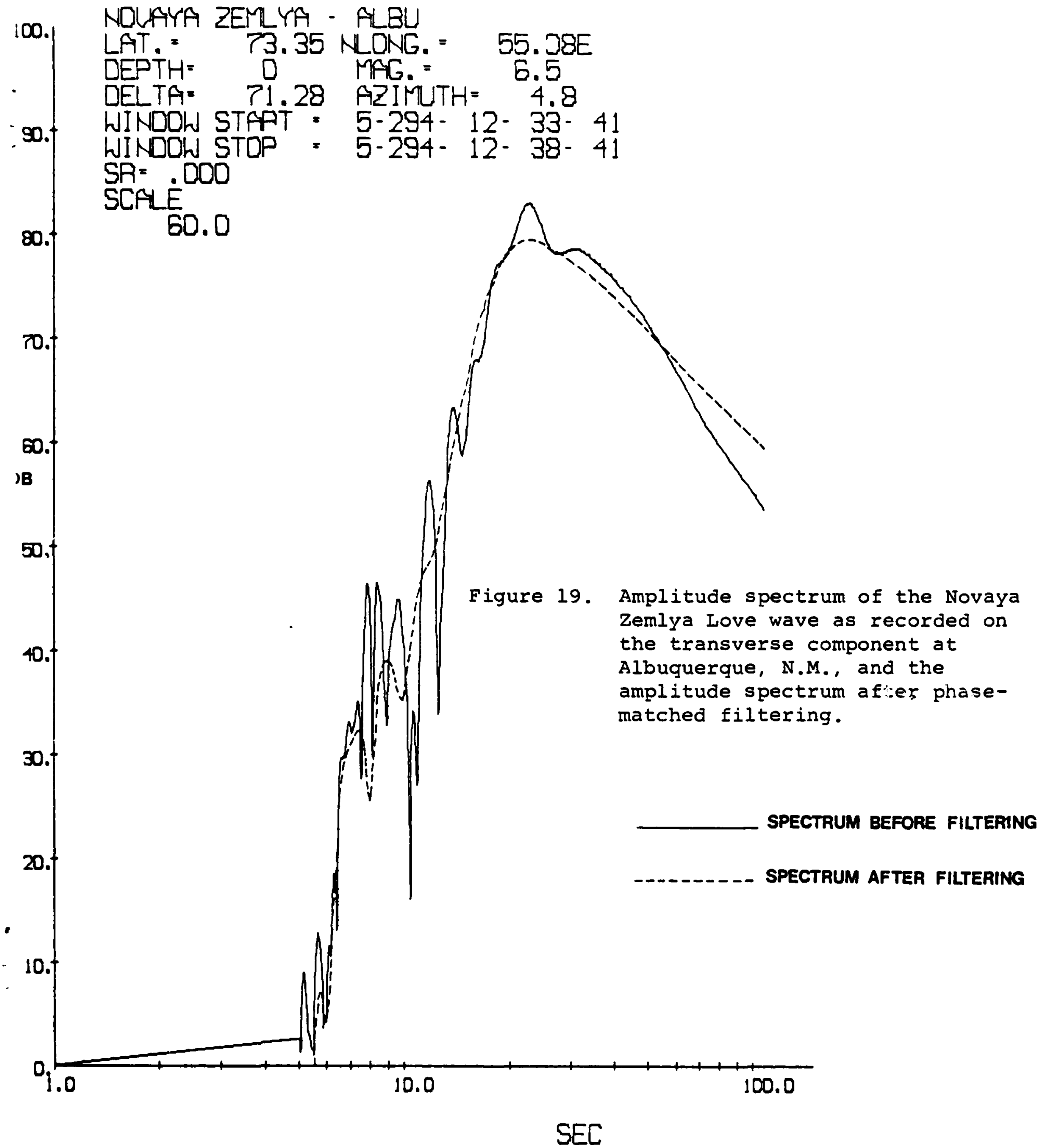


Figure 19. Amplitude spectrum of the Novaya Zemlya Love wave as recorded on the transverse component at Albuquerque, N.M., and the amplitude spectrum after phase-matched filtering.

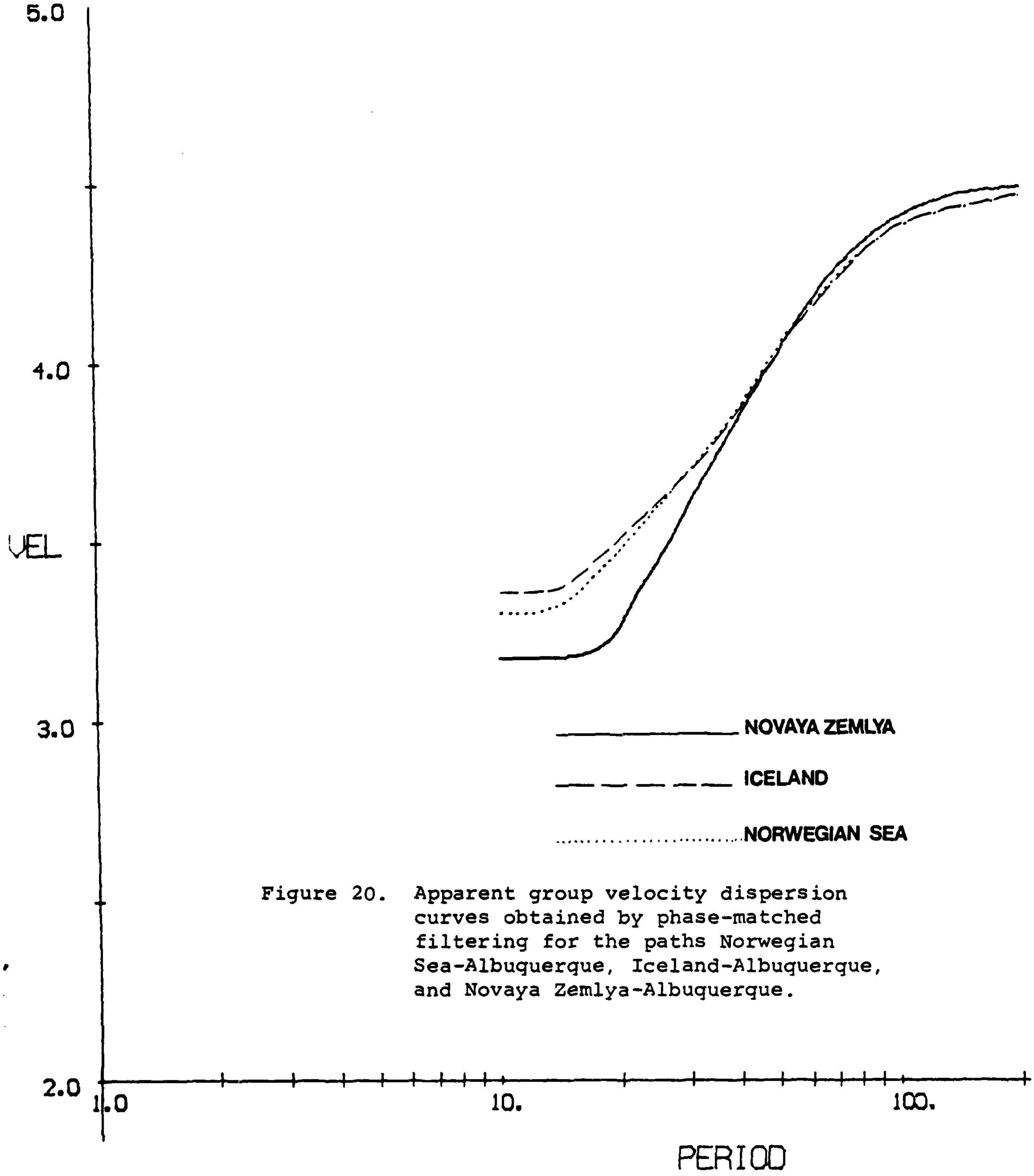


Figure 20. Apparent group velocity dispersion curves obtained by phase-matched filtering for the paths Norwegian Sea-Albuquerque, Iceland-Albuquerque, and Novaya Zemlya-Albuquerque.

DISCUSSION

The three seismic events analyzed in this study demonstrate that in many cases attempts to utilize Love waves in studies of earthquake focal mechanisms or propagation path characteristics will fail because of the effect of interfering wave trains. Not only are high quality horizontal data, such as provided by the Seismic Research Observatories, required, but also some technique to eliminate interfering wave trains is essential for unbiased Love wave analysis. Phase-matched filtering provides the capability to resolve the composite Love wave into its various constituent wave trains so that each may be studied separately.

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